

SDSS J120923.7+264047: A new massive galaxy cluster with a bright giant arc

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ABSTRACT

Highly magnified lensed galaxies allow us to probe the morphological and spectroscopic properties of high-redshift stellar systems in great detail. However, such objects are rare, and there are only a handful of lensed galaxies which are bright enough for a high-resolution spectroscopic study with current instrumentation. We report the discovery of a new massive lensing cluster, SDSS J120923.7+264047, at $z = 0.558$. Present around the cluster core, at angular distances of up to $\sim 40''$, are many arcs and arc candidates, presumably due to lensing of background galaxies by the cluster gravitational potential. One of the arcs, $21''$ long, has an r -band magnitude of 20, making it one of the brightest known lensed galaxies. We obtained a low-resolution spectrum of this galaxy, using the Keck-I telescope, and found it is at redshift of $z = 1.018$.

Key words: gravitational lensing — galaxies: clusters: individual (SDSS J120923.7+264047 — galaxies: high-redshift)

1 INTRODUCTION

High redshift galaxies ($z \gtrsim 1$) are out of reach for current high-resolution spectrographs. Fortunately, such galaxies may be highly magnified, when lensed by galaxies or cluster of galaxies, making them bright enough for high-resolution spectroscopic studies. However, high magnification lensed galaxies are rare, and only small number of targets suitable for high-resolution spectroscopic studies are known. Among these are: MS1512–cB58 (Yee et al. 1996), with $r = 20.4$ mag at $z = 2.72$; an $r = 20.3$ mag Lyman break galaxy at $z = 3.07$ (Smail et al. 2007); and finally a highly magnified galaxy, at $z = 2.73$, with $r = 19.2$ mag (Alam et al. 2007). Studies of these objects (e.g., Teplitz et al. 2000; Pettini et al. 2000; 2002; Baker et al. 2004; Schaerer & Verhamme 2008) provided valuable information on their metallicity and inter-stellar medium.

In this paper we report on the discovery of a previously unknown rich cluster of galaxies at $z = 0.558$. The cluster containing a bright “giant arc”, which is an appropriate target for high-resolution spectroscopic studies. In addition, the cluster, which has a considerable Einstein radius of probably $\sim 20 - 40''$, contains a large number of additional arcs and lensed galaxies. This cluster is probably as rich as the Abell 1689 lensing cluster (Broadhurst et al. 2005), and therefore

it is an excellent target for detailed strong lensing and weak lensing modeling (e.g., Bradač et al. 2006; Halkola et al. 2006).

The outline of this paper is as follows. We describe the observations in §2 and in §3 we discuss the cluster and arcs along with their measured properties. Finally, we briefly discuss the results in §4.

2 OBSERVATIONS

The discovery of the cluster and arcs described in this paper, was made as part of a survey for large separation lensed quasars (e.g., Maoz et al. 1997; Ofek et al. 2001; Phillips et al. 2001; Inada et al. 2003; Oguri et al. 2004; Inada et al. 2006; Oguri et al. 2008), among Sloan Digital Sky Survey (SDSS; York et al. 2000) photometrically selected quasars. This search will be described elsewhere. Our search uncovered a previously unknown cluster of galaxies in an SDSS image. In addition to the cluster, a giant arc was clearly visible near the cluster, in the relatively shallow SDSS images.

On UTC 2008 Jan 04, we obtained 5×220 s g -band and 5×180 s R -band images of the cluster environment using the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck-I telescope, under seeing of $0.6''$. The combined Keck R -band image is presented in Figure 1, and the combined g -band image is presented in Fig. 2. The

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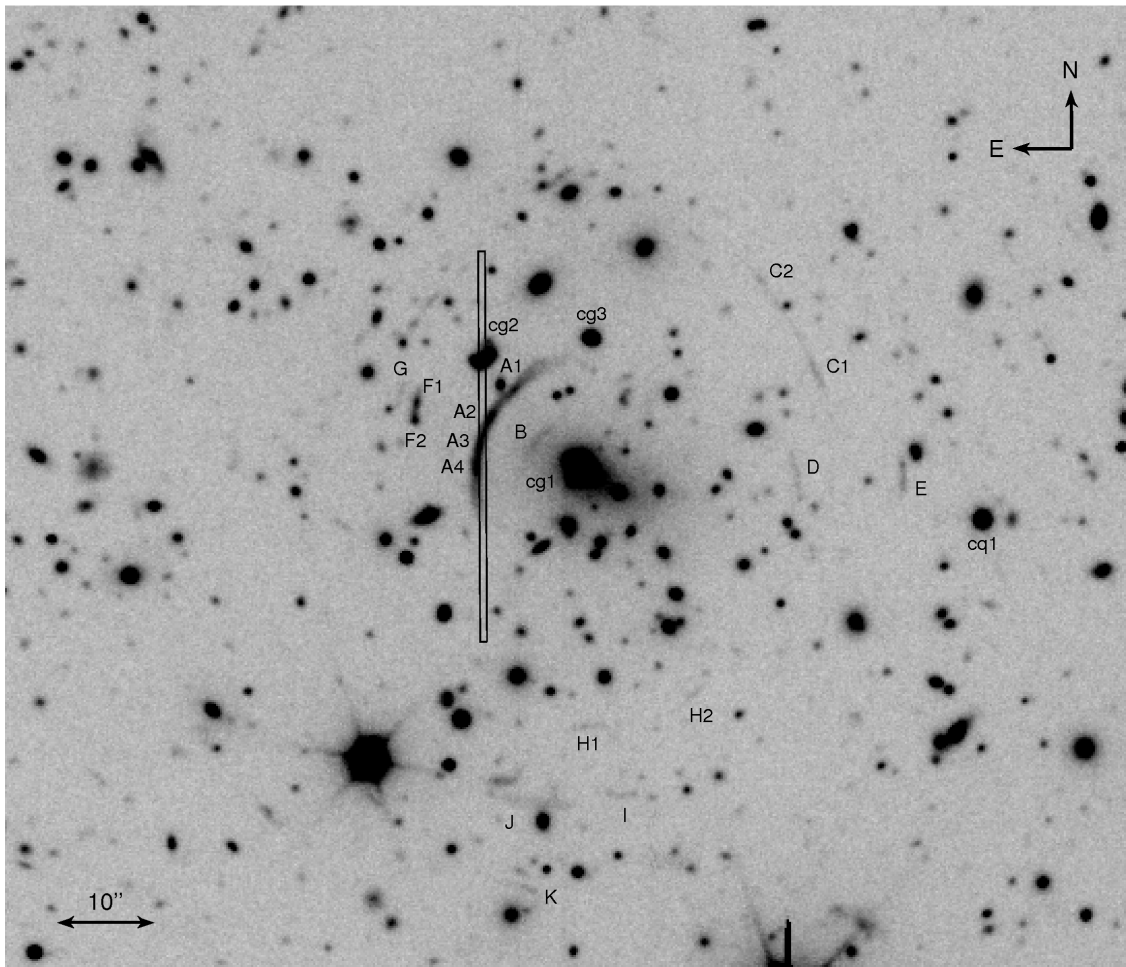


Figure 1. *R*-band image of SDSS J120923.7+264047, obtained with LRIS mounted on the Keck-I 10 m telescope. Objects labeled by A1...K are candidate arcs. The properties of the labeled arc candidates are listed in Table 1. Also labeled are: the cluster bright galaxy (cg1; SDSS J120923.68+264046.7) which is at $z = 0.558$; (cg2; SDSS J120924.41+264057.8) at $z = 0.542$; (cg3; SDSS J120923.60+264059.9) at $z = 0.542$; and a bright SDSS quasar (cq1; SDSS J120920.61+264041.2), at $z = 1.555$. The quasar, cq1, which has an *r*-band magnitude of 19.2 is found $41''$ from the bright cluster galaxy, so most probably it is not strongly lensed by the cluster. Also marked is the position (and actual width) of the slit we used to obtain the spectrum of the arc.

images were calibrated astrometrically using six objects appearing in both the Keck and SDSS images. The solution root-mean-square (RMS) is better than $0.1''$ in both axes and both images. In Table 1 we give the positions and photometry of the main arcs detected in the images. We have measured the magnitude of each arc, by combining all the light within a polygon defined by the SExtractor segmentation (Bertin & Arnouts 1996). In case SExtractor broke an arc to several segments, we combined the light within these segments. The SExtractor detection threshold was set to about 2σ above background.

On the same night, using LRIS–Atmospheric Dispersion Compensator we also obtained a 1300 s spectrum of the bright giant arc, labeled A1...A4 in Fig. 1. We used a $0.7''$ slit with the 5600 \AA dichroic; the 400/3400 grism on the blue side; and the 400/8500 grating, centered on 7693 \AA , on the red arm. The slit position angle was set to 180.2° , in order to include also the blue (SDSS $g - r \approx 0.6$) galaxy labeled cg2 in Fig. 1. The spectrum was flux calibrated using observations, obtained on the same night, of the spectropho-

tometric standard Hz2 (Turnshek et al. 1990). The spectrum of arc A is shown in Fig. 3. We also obtained using the same setup, on UTC 2007 Dec 15, a 1500 s-exposure spectra of the galaxies cg2 and cg3. The spectral reduction was done using tools in the MATLAB environment (Ofek et al. 2006). The spectra of the galaxies cg2 and cg3 are shown in Fig. 4.

3 THE CLUSTER AND ARCS

The Keck *R*-band image of the cluster is presented in Fig. 1. In this figure, it is possible to identify many arc candidates, most of which are labeled (A to K). We list the properties of these arcs and arc candidates in Table 1. The most prominent arc in this system, labeled as A1–A4 in Fig. 1, is very large and bright. This arc is located about $11''$ East of the brightest cluster galaxy, and its length is $21''$. The spectrum of the arc, presented in Fig. 3, shows a single strong emission line and several absorption features, at a probable redshift of $z = 1.018$. We note that there is also an indication for

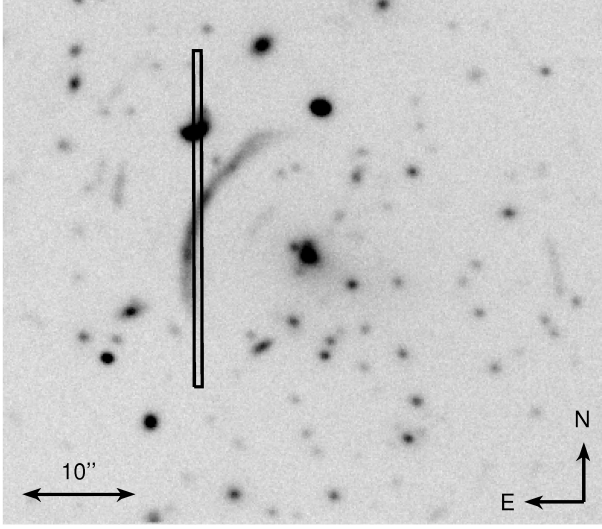


Figure 2. *g*-band image of SDSS J120923.7+264047, obtained with LRIS mounted on the Keck-I 10 m telescope. See Fig. 1 for details.

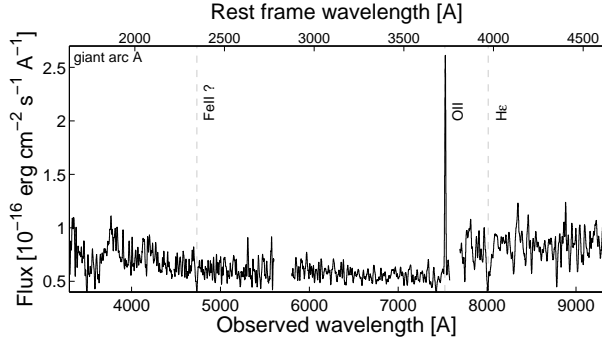


Figure 3. The Keck/LRIS spectrum of the giant arc A (Fig. 1; Tab. 1). The detection of several lines indicates a redshift of 1.018.

a Balmer decrement around 7700 Å (observed wavelength). The redshift is based on the detection of a single emission line. Therefore, we attempted to look for other possible explanations for this emission line, and we did not find any other reasonable redshift solution. Moreover, the Einstein radius increases with source redshift. Therefore, the relatively small Einstein radius of arc-A implies that it is at

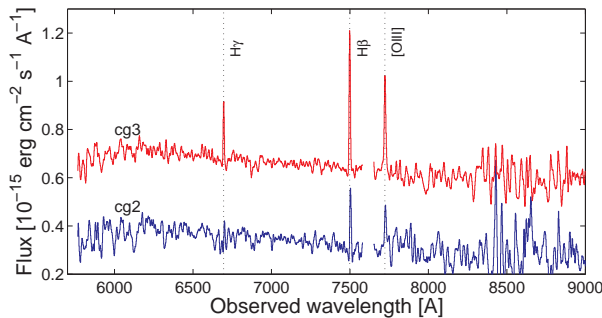


Figure 4. The Keck/LRIS spectrum of the galaxies cg2 and cg3. The galaxies are at redshift of 0.542. For clarity, the spectrum of cg3 is shifted upward by $4 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$.

Name	R.A. J2000	Dec. J2000	g mag	r mag
A1	12:09:24.19	+26:40:54.7		
A2	12:09:24.38	+26:40:51.9		
A3	12:09:24.46	+26:40:49.1		
A4	12:09:24.48	+26:40:47.0		
A			20.3	20.0
B	12:09:24.00	+26:40:49.9		24.0
C1	12:09:21.91	+26:40:56.9		24.8
C2	12:09:22.31	+26:41:05.9		24.9
D	12:09:22.04	+26:40:46.5		24.5
E	12:09:21.22	+26:40:45.8		24.2
F1	12:09:24.94	+26:40:53.5		23.4
F2	12:09:24.96	+26:40:51.6		23.7
G	12:09:25.06	+26:40:54.5		25.2
H1	12:09:23.65	+26:40:20.2		25.6
H2	12:09:22.82	+26:40:23.5		26.0
I	12:09:23.38	+26:40:13.2		25.3
J	12:09:24.17	+26:40:12.6		24.5
K	12:09:24.10	+26:40:03.6		24.7

Table 1. Positions and approximate magnitudes of most of the arc candidates detected in the Keck *R*-band image (Fig. 1). The magnitudes are approximate, and have typical uncertainties of 0.3 mag. The astrometry was performed relative to the SDSS.

relatively low redshift. Its redshift, which places it in the background of the cluster, along with its unique appearance, confirms the nature of this arc as a lensed galaxy.

The Einstein radius of a system scales like $[D_{ls}/(D_l D_s)]^{1/2}$, where D_{ls} , D_l and D_s are the angular diameter distances between the lens and source, observer and lens, and observer and source, respectively (e.g., Narayan & Bartelmann 1996). Therefore, for the system discussed here, we expect that the Einstein radius for a $z \approx 4$ system to be about 30% larger than for a $z = 1$ system¹. This suggest that at least some of the arclets further away from the center of the cluster are most probably strongly lensed background galaxies at higher redshifts.

The brightest cluster galaxy, cg1 (SDSS J120923.69+264046.7) in Fig. 1, was observed spectroscopically by the SDSS, and we find it to be at a redshift of 0.558. As mentioned before, we also obtained a spectrum of the blue galaxies marked cg2 (SDSS J120924.41+264057.8) and cg3 (SDSS J120923.60+264059.9) in Fig. 1. We measured a redshift of 0.542 to these galaxies using the H β (4862.7 Å) and [OIII] (5008.2 Å) emission lines present in their spectra. Given the redshift of the brightest cluster galaxy, we suggest that the cluster redshift is 0.558. However, confirmation of this redshift requires a redshift measurement for additional galaxies in this region.

¹ Assuming 3rd year WMAP cosmological parameters: $\Omega_\Lambda = 0.716$, $\Omega_m = 0.268$, $H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$; Spergel et al. (2007).

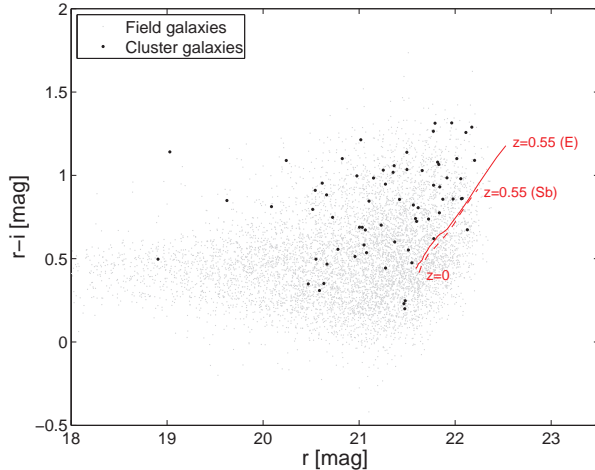


Figure 5. The color-magnitude diagram of SDSS galaxies in the direction of the cluster. The black circles represent galaxies found with $2'$ from the cluster bright galaxy. For comparison, we also show all the SDSS galaxies found between $5'$ and 1° from the cluster bright galaxy (gray dots). The solid (dashed) red-lines display the locus of Elliptical (Sb) galaxies as a function of redshift. These lines take into account the Galactic extinction ($E_{B-V} = 0.019$ mag) in the direction of the cluster (Schlegel et al. 1998; Cardelli et al. 1989). The galaxies colors as a function of redshift are based on synthetic photometry of galaxy templates from Kinney et al. (1996). The synthetic photometry was performed using the code of Poznanski et al. (2002).

4 DISCUSSION

Strong and weak lensing are being used to trace the mass distribution of galaxy clusters. However, detailed modeling of the mass distribution of the cores of galaxy clusters requires the identification of multiple images of lensed sources. Such an identification needs good multi-band color information, or/and good spatial resolution (e.g., Broadhurst et al. 2005; Sharon et al. 2006). Indeed we are planning additional multi-band observations of this cluster, which will enable a detailed modeling of the cluster gravitational potential.

To confirm the presence of the cluster, in Fig. 5 we show the color magnitude diagram for SDSS galaxies found with $2'$ from the cluster bright galaxy (black circles). For comparison, we also show all the SDSS galaxies found between $5'$ and 1° from the cluster bright galaxy (gray dots). The solid (dashed) red-lines display the locus of Elliptical (Sb) galaxies as a function of redshift. These lines take into account the Galactic extinction ($E_{B-V} = 0.019$ mag) in the direction of the cluster (Schlegel et al. 1998; Cardelli et al. 1989). It is evident, that in the cluster direction there is an excess of high-redshift galaxies, relative to the field.

At the approximate position of the bright cluster galaxy, we find a known ROSAT source (Voges et al. 2000). Using the PIMMS webtool², we converted the ROSAT/PSPC count rate to an unabsorbed flux of 6.9×10^{-13} erg cm⁻² s⁻¹, assuming a Galactic neutral Hydrogen column density of 1.8×10^{20} cm⁻² (Dickey & Lockman 1990; Kalberla et al. 2005) and a power-law spectrum with a photon index of $\Gamma = 1$ (assuming thermal optically thin Bremsstrahlung).

Given the luminosity distance to the cluster, this flux implies a luminosity of $\sim 8 \times 10^{44}$ erg s⁻¹ in the 0.1–2.4 keV band. Using the X-ray luminosity-mass relation given by Reiprich & Böhringer (2002), we estimate that the M_{200} mass³ of the cluster is approximately $10^{15} M_\odot$.

We can also estimate the mass of the cluster from its Einstein radius:

$$\theta_E = \left[\frac{4GM(\theta_E)}{c^2} \frac{D_{ls}}{D_i D_s} \right]^{1/2}. \quad (1)$$

The Einstein radius is a robust measure of the lens mass within this radius. Although we did not identify the counter-image(s) of arc-A we can estimate the Einstein radius based on the distance of the arc from the cluster bright galaxy ($\sim 11''$). Using Eq. 1 we estimate that the total mass enclosed within 90 kpc (i.e., the Einstein radius, $11''$, at $z \approx 1$) is $\sim 6 \times 10^{13} M_\odot$.

To summarize, we report on the discovery of SDSS 120923.7+264047 – a massive cluster of galaxies at $z = 0.558$. The cluster hosts many prominent arcs, including a giant arc with R -band magnitude of 20.0, at $z = 1.018$. Moreover, presumably the cluster has a large Einstein radius, suggesting that it is one of the richest strong lensing clusters known.

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³ M_{200} is the mass enclosed within r_{200} , which is the radius in which the mean density equals 200 times the mean density of the Universe (e.g., Navarro, Frenk, & White 1997).

² <http://cxc.harvard.edu/toolkit/pimms.jsp>

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